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THEORETICAL CONSIDERATIONS OF THE GENESIS OF ORE DEPOSITS

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Nothing is more noticeable in the history of mining geology than the change which has taken place in the last half-century in the prevailing opinions as to the origin of ore deposits. We may leave out of account the absurdities of Wernerism and most of the earlier speculations of the Plutonist school. Scientific ideas as to the genesis of ores may be said to date from the publication of Breithaupt's epoch-making little book in 1849.[1] Here in the idea of paragenesis we have the germ of modern speculations on this subject. For long, however, the theory of the aqueous origin of all ore deposits held sway in its various forms, one of the best-known of which was the famous lateral-secretion theory. Even yet something very like this theory is held to furnish the best explanation of the origin of certain types, as for example the lead-zinc ores of the Mississippi Valley and other similar deposits. The brilliant writings of Pošepný also did much to perpetuate the reign of water. Nevertheless, at the present time no one will be found to deny that many and important ore deposits are of direct igneous origin. As a matter of fact igneous and aqueous origin are by no means incompatible. It may at once be admitted that watery solutions may be produced direct from magmas. Of this

[1] Breithaupt, *Die Paragenesis der Mineralien*, Freiberg, 1849.

we have abundant evidence in the steam that accompanies volcanic eruptions, and the geysers and hot springs belonging to the later stages of igneous activity in many parts of the world, such as the Yellowstone Park, Iceland, and New Zealand. At Steamboat Springs, Nevada, ores are now visibly being formed by hot springs which must derive their heat from intratelluric sources. It is natural to suppose, therefore, that many of the ancient ore deposits have been formed in a similar way. The common association of ores with propylitization and certain other types of rock-alteration points in the same direction.

Moreover, ore minerals occur in rocks undoubtedly igneous as well as in lodes and veins. Cassiterite is found as an original mineral in granites, in pegmatites, and in quartz veins in undoubted and visible connection with granites. The same applies to its constant companions wolframite and molybdenite. Gold is known in almost every conceivable geological situation of almost every age. Chromium and platinum are found beyond doubt as original constituents of ultrabasic rocks such as peridotites and serpentines. Magnetite and ilmenite have segregated in enormous masses from plutonic intrusions, and so on indefinitely. A great part of the rich mineralization of Mexico and South America is in obvious and visible connection with the great volcanic outbursts ranging from late Cretaceous to modern times. It is clear that a vast number of the most valuable ore deposits are of direct igneous origin. In many other instances, though the connection is not so clear, it is still highly probable or indeed certain.

Nevertheless, although the main fact in its broadest outlines is established, considerable doubt still remains as to the mechanism of the processes by which the concentration and deposition of the ores has been effected, and the underlying and fundamental reasons for these processes. Another highly important aspect of the subject is the distribution in space and time of the different types of mineralization and their relation to crust disturbances and various petrographic types. This in the broadest view is the scope of the study of metallogenesis.

Hitherto it has not been found possible to devise a really satisfactory and logical classification of ore deposits on a genetic

basis. This impossibility is inherent in the nature of the subject, since in nature there exist no sharply defined categories, no pigeon-holes into one of which every type will fit. It is the intermediate and transitional types that are the bugbear of any such attempt. Nevertheless there are some basic facts that may be used as a groundwork for generalization. In the first place we have certain ores occurring as original minerals in igneous rocks, and as disseminations and magmatic segregations whose origin from magmas is beyond doubt. Also there are the innumerable instances of ore-bearing pegmatites which can also be assigned with safety to the same origin. A great number of contact and replacement deposits also undoubtedly owe their metal content to transfer from intrusive masses.

It is, however, when we come to the large and highly important class of deposits described in general terms as veins and lodes that difficulties begin to manifest themselves. These undoubtedly grade on the one hand into the magmatic deposits, while on the other hand some of them show distinct evidence of having been formed near the earth's surface at the ordinary temperature and pressure. In dealing with the doubtful members of this group we have to take into account not only the characters of the deposits themselves, but all the attendant circumstances which may throw any light on their origin, such as geographical distribution, relation to sedimentary and other formations of known age, and to the structure, disposition, and character of the surrounding rocks; in short, their geological features. It is the geology of the ore deposits that will throw most light on their origin.

As an example let us take the mining region of western Cornwall, one of the most highly mineralized districts of the world, especially as regards the number of metals found. Here cassiterite occurs as an original mineral in the granite, in pegmatites, in greisens and other pneumatolytic modifications of the granite, in quartz-porphyry dikes, and, most important of all, in a vast number of lodes and veins which chiefly congregate near the contact of granite and slate, almost invariably passing from one rock to the other without interruption. The lodes also show every possible degree of pneumatolytic alteration. Besides cassiterite they

contain wolframite, most abundantly in a comparatively narrow zone near the granite-slate contact. Arsenopyrite is also abundant, and in the upper parts of the lodes, farther away from the granite, tin gradually gives place to copper. Other metals, such as molybdenum, silver, antimony, bismuth, and uranium, are also found, while lead and zinc are abundant in a later series of lodes, usually more distant from the contact. Among the gangue minerals tourmaline, topaz, and fluorspar are abundant. Here the connection of the tin-copper mineralization with the granites and their pneumatolytic phase is obvious. The age of this is also definitely fixed, since the granites cut Upper Carboniferous rocks and the Permian strata are not metamorphosed. The whole of this igneous cycle is a direct consequence of the Armorican crust disturbances which had such an important influence in molding the geological structure of west-central Europe. Very similar phenomena are to be seen in Brittany, in Spain and Portugal, and in the Erzgebirge on both sides of the frontier between the German Republic and Czecho-Slovakia: all of these are broadly contemporaneous with the similar occurrences in Cornwall.

Here we have a clear example of a metallogenetic province, showing a definite association of mineral deposits of a peculiar type with a phase of igneous intrusion dependent on a particular set of earth movements. The number of metals present is very large, but the most characteristic are tin and tungsten, and a special feature observed in Cornwall, Bohemia, and Portugal is the presence of uranium.

Turning now to another region of the Old World, we find a great development of tin ores in the Malay peninsula, in Banka and Billiton, and on the eastern side of the Australian continent from Queensland to Tasmania. In Lower Burma (Tavoy) we find a little tin and much tungsten, so that this evidently forms a slightly varying extension of the same field, a local facies. This tin-bearing region stretches parallel to the great Malayan arc and its continuation into Australia and the mineralization is closely connected with the intrusion of granites, probably of Permo-Carboniferous age. Furthermore, this great province is divided up into subprovinces characterized by special mineral

associations, namely, in Tavoy, dominance of tungsten; in the Malay peninsula, Banka, and Billiton, dominance of tin alone; in Queensland, tin, tungsten, molybdenum, bismuth; in New South Wales, tin, tungsten, and molybdenum; in Tasmania, mainly tin.

The second most important tin-producing country of the world is Bolivia. Here along the Cordilleran chains, in association with the great Tertiary volcanic activity, we find extraordinarily rich veins carrying tin, tungsten, bismuth, and silver; a remarkable and apparently unique type.[1] These veins present features of great interest from the theoretical point of view. Three chief types of veins can be recognized, as follows:

a) Tin-bismuth veins with tourmaline and other pneumatolytic minerals, associated with deep-seated granites.

b) Tin-bismuth-silver veins, carrying most of the tin as complex sulphides, stannite, etc., associated with hypabyssal porphyry intrusions.

c) Silver veins without tin, associated with extrusive volcanic rocks.

A noteworthy feature is the occurrence of the tin in type (*b*) mainly as complex sulphides associated with argentiferous tetrahedrite and sulphosalts of copper, lead, bismuth, arsenic, and antimony. There is thus a distinct gradation in the metal contents of the veins, minerals with boron and fluorine occurring in quantity only in the high-temperature veins associated with granites. Thus the temperature-depth relations of tin and silver are clearly shown.

In all these cases there can be no possible doubt of the association of the tin and other metals with igneous rocks. When we turn to other metals the facts are equally striking. It is impossible to enumerate all of them, but a few examples must suffice, and these may be taken as typical of the rest. It has long been known that platinum has its original home for the most part in peridotites and their alteration product, serpentine, and to a less extent in certain nickel-bearing and other eruptives to be mentioned presently; in short, in ultrabasic and basic rocks. The peridotites also commonly contain large quantities of chromite and also chrome-bearing spinels: hence the presence of chromite is a useful

[1] Davy, *Econ. Geol.*, Vol. XV (1920), pp. 463–96.

indicator of the possible presence of the platinum metals. In the basic rocks also we find large masses of iron ore commonly rich in titanium, either as ilmenite or as titaniferous magnetite. The presence of titanium is specially characteristic of the basic group. Another type of great scientific interest and commercial importance is seen in the great segregations of nickeliferous sulphides found in connection with norites and gabbros, as at Sudbury, Ontario, and Insizwa in Griqualand East. Whatever may be the actual mechanism of the Sudbury nickel deposit, its close connection with the norite intrusion will hardly be denied, and at Insizwa the concentration of the sulphide by some form of differentiation seems clear. In association also with basic rocks, especially with gabbros, are found great masses of pyrite, as at Rörös in Norway, and the cupriferous sulphides of the Huelva district (Rio Tinto and others) also belong here.

In all these cases of the occurrence of ores in basic magmas one point is worthy of special attention, namely, that the ores occur either as disseminations in the rock itself (platinum and chromium in part) or as segregations separated from the magma either by gravity, by diffusion to the margin, or by separation of immiscible liquids. The ore bodies therefore lie either within the intrusion as disseminations, schlieren, or irregular patches, or as a definite layer at its base, or as separate intrusions, often laccolithic in form. Here there is no separation of the ores in pegmatites and all the innumerable varieties of mineral veins, as with the acid rocks, while pneumatolytic effects are subordinate, or more commonly entirely absent. In conformity with this, metamorphic and metasomatic effects are also much less marked. The most characteristic type of basic pneumatolysis is scapolitization, which appears to correspond to tourmalinization in acid rocks, while the concentration of apatite in some instances may also be referred here.

Here another generalization of fundamental importance may be made: the ore segregations of the basic rocks are usually the *first* fraction of the magma to crystallize, those of the acid rocks are usually the *last* fraction. In neither case is the statement invariably true, but exceptions are as a rule due to special causes.

For example, the great iron-ore masses of Kiirunavaara and Luossavaara, as described by Daly, have been formed by the sinking of early-crystallized magnetite in a quartz-porphyry magma. The case of iron ore is, however, exceptional in that it is not specially characteristic of any particular magma, but is of more or less universal distribution.

Although this generalization must not be pushed too far, it is certainly true in its broad outlines. The reason for it is to be found in the presence in, or absence from, the crystallizing and differentiating magma of substances capable of combining with the metals to form volatile compounds, such as fluorine, boron, and especially water. We have every reason to believe that basic magmas do not contain much water; at any rate it is possible to produce basic rocks artificially from dry melts, whereas with acid rocks this cannot be done: some flux is required to insure the crystallization of quartz or orthoclase or hornblende. Such fluxes collect always in the acid fractions of a differentiate, there lowering freezing-points and in particular facilitating the concentration of metals in the last residue of the magmatic solution, which must always tend toward, if it does not actually reach, the composition of the multiple eutectic of the complex solution. In some simple cases the eutectic of quartz and felspar is actually reached, as seen from the simultaneous crystallization of quartz and felspar in graphic pegmatites.

The case of iron is a rather exceptional one, since it is found in considerable amount in connection with igneous rocks of both acid and basic types. The iron-ore masses of Sweden have already been mentioned: here the iron occurs as magnetite, occasionally as hematite, at all events as iron oxides only, and this is the common type in acid rocks. In the basic segregations, however, the state of affairs is generally different: in a great many ultrabasic rocks we find ferrous oxide combined with chromium as chromite, or with magnesium and aluminium in addition as picotite or some allied chromiferous spinel. In the felspathic basic rocks, on the other hand, the greater part of the iron is in some state of combination with titanium, either as ilmenite or as a titaniferous magnetite, whatever that may really be. Again, in the basic rocks iron is

found frequently as sulphide segregations, either with or without copper, nickel, and cobalt. Thus it is seen that although iron as an element is common to both ends of the series, nevertheless it occurs typically in a different state of combination in each.

Having thus arrived at the fundamental generalization that there are two principal groups of ore segregations of very early and very late consolidation respectively, we must now proceed to consider in more detail what particular type of differentiation may be applied in explanation of each.

At the present time five different sets of causes are commonly put forward in explanation of the varied set of phenomena comprised under the head of differentiation, including in this term not only the production of heterogeneity in single intrusions, but also the separation of minor magmas of varying composition from one original magmatic solution. These may be summarized as follows:

a) Marginal concentration of minerals of high freezing-point by diffusion of liquid molecules immediately preceding and during crystallization.

b) Differentiation by gravitational sinking or rising of crystals in a solidifying magma.

c) Separation of a magma into two or more immiscible or partially miscible layers.

d) Assimilation by stoping with its attendant fluxing effects.

e) Squeezing out of liquid residue from a crystalline sponge or network.

This is not the place to discuss the evidence as to the competence of each of these processes as a general factor in differentiation. It is probable that all are applicable in different cases and under different sets of conditions: we have only to consider which of them can be invoked to explain the various types of ore occurrence here already briefly alluded to. It is evident that in the two great groups of ores of early and late consolidation very different physical conditions must prevail, especially as regards temperature and presence of the so-called mineralizing agents or fluxes. In the early group the temperatures must be very high, and we have reason to believe that in the basic rocks fluxes are unimportant; hence it appears that any one of the first three categories should be specially applicable.

Of the first type we have an excellent example in the marginal phase of the gabbro of Carrock Fell, as described by Harker. Here a well-marked segregation of titaniferous iron ore is found along both steeply inclined margins of a laccolith of considerable size, believed to be still more or less in the same position as when intruded. From the figures and description given by Harker it is clear that gravity is excluded, and the only possible explanation is some kind of diffusion to the cooling surfaces during crystallization. The concentration is not very strongly marked, as the most concentrated type of ilmenite-gabbro has only about 25 per cent of iron ore, but at any rate the principle is clear. A very peculiar type is the great mass of titaniferous iron ore at Taberg in Sweden, which forms the central portion of a boss of ultrabasic rock, usually described as hyperite, that is, olivine-norite in modern terms. The reason for this reversal of the normal sequence is unknown.

It will doubtless be generally conceded that it must be difficult on field evidence alone to distinguish between cases of heterogeneity due to gravity-sinking and to immiscibility in the liquid state. In both cases, on complete solidification the heavier rock will be found below, and owing to the high viscosity of fused silicates no very sharp line of demarcation is likely to be seen. It is moreover highly probable that in some instances both causes have been operative. Bowen has brought forward much evidence in support of differentiation by gravity-sinking, and Vogt long ago showed that fused silicates and sulphides possess very strictly limited miscibility.[1] In the well-known instances of Sudbury and Insizwa we have thick intrusions ranging from acid or intermediate at the top to basic or ultrabasic below, with a well-marked layer of sulphides at the bottom. Here it may be suggested that the gradation in the silicate rock is due to gravity with an immiscible separation of sulphide at the base. It seems pretty clear from Daly's latest observations that the concentration of magnetite and apatite at Kiruna is due to gravity-settling of rather large units of differentiation, since many blocks of ore have been caught and fixed at higher levels by increasing viscosity. The occurrence of limited miscibility in silicate solutions is a much disputed point,

[1] Vogt, *Die Silikatschmelzlösungen*, Part I (Kristiania, 1903), p. 96; "Die Sulfid-Silikatschmelzlösungen," *Norsk geologisk tidsskrift*, 1917.

as to which we have as yet no absolute evidence, but it seems quite clear that this cause may be legitimately invoked to explain cases of magmatic sulphide segregations. Vogt has shown by quantitative determinations that the mutual solubility of norite magmas and sulphides is very small indeed; at 1300° C. and one atmosphere, less than 0.5 per cent in the case of pyrrhotite, while copper and nickel sulphides are practically insoluble in norite melts. Moreover, it is improbable that these relations are seriously altered by high pressures.[1]

Up till the present time we have no definite information as to the part played by assimilation and stoping in the formation of ore deposits. In the nature of things such a process would necessarily be difficult to detect, since it would itself destroy its own traces. It is possible, however, that some masses of ore in acid and intermediate rocks may have been introduced in this way, such as the deposits of iron, copper, and gold in magmas of the monzonitic and dioritic facies. This, however, is pure speculation with no tangible evidence to support it. It seems possible that in the earliest solid crust of the earth, afterward remelted, there may have been segregations of metallic ores, afterward reabsorbed and differentiated, as suggested by Morrow Campbell.[2] As to this, likewise, there can in the nature of things be no positive information. It is known that in some localities, for example, southwestern Norway, there is a notable concentration of minerals of the rare earths into syenitic pegmatites, as described by Brögger.[3] If we accept Daly's theory of the origin of alkaline rock types by the fluxing effects of assimilated limestone in normal magmas, it would seem to follow that the concentration of the rare earths here must also have resulted directly from the assimilation. On this question as a whole further information is needed, as few observations are available on the occurrence of ores in connection with highly alkaline magmas.

With regard to the squeezing out of liquid residues from partially consolidated rocks, like water from a sponge, as so graphically

[1] Vogt, *Norsk geol.tidsskr.*, 1917, p. 77.

[2] *Bull. Inst. Min. Met.*, October, 1920, p. 3.

[3] Brögger, *Zeitschr. für Kryst.*, Vol. XVI (1890).

pictured by Harker,[1] this cause may undoubtedly be invoked to explain the separation of pegmatitic material from cooling granites under earth pressure. This process has given rise to areas of pegmatitic permeation, as described by Barrow,[2] in the south-eastern Highlands of Scotland. It is hardly necessary to point out again that pegmatitic mother-liquors often carry notable amounts of ore minerals, and in many instances this seems the most reasonable explanation of ore-bearing pegmatites.

From the foregoing brief and imperfect summary it appears that ore deposits may arise from all or any of the physicochemical processes that have been invoked to explain the origin of heterogeneity in igneous rocks. In some cases one is applicable, in some cases another, but none are apparently excluded on a priori grounds. This variety of origins is only what we should expect from the great differences observable in the characters of the deposits themselves. Here again a correlation can be traced between the nature of the effective process and the physical properties of the molten magmas of different composition and especially the degree of viscosity. Generally speaking, it is admitted that basic magmas are more liquid than normal acid magmas in spite of the higher proportion of water in the latter. Hence differentiation by diffusion, gravity, and immiscible separation are more marked in the basic class, owing to lower viscosity. It is only in the differentiated and concentrated last residues of the acid class that the solution becomes readily mobile and lends itself to formation of veins and pegmatitic permeation. A similar effect is produced by assimilated fluxes in certain cases. These considerations lead again to the same conclusion as before, namely, that the ore deposits of the basic rocks are marginal and basal, or included segregations of a streaky nature if convection currents have been active, while from the acid fluxed magmas are formed veins and lodes in all their varieties, either in fissures in the rock itself, often congregated near its roof, especially in subsidiary domes and cupolas,[3] or actually external to the intrusion, filling fault planes and other fissures and zones of weakness in the

[1] Harker, *Natural History of Igneous Rocks* (1909), p. 323.

[2] Barrow, *Quart. Jour. Geol. Soc.*, Vol. XLIX (1893), p. 330.

[3] Butler, *Econ. Geol.*, Vol. X (1915), pp. 101–22.

country rock. The endless varieties of contact deposits are not here taken into account in detail, but it may perhaps be said that they are more characteristic of acid intrusions, doubtless owing to the abundance of mineralizers, which act as carriers for the metals.

Having thus considered in general terms the phenomena of differentiation and concentration in igneous rocks in their bearing on the origin of ore deposits, it remains to see whether it is possible to draw up a schematic classification on this basis. If this can be done it would constitute a genetic classification of ore deposits in the strictest sense of the word; such a classification, if presented in a graphic form, may be regarded as a genealogical tree of the ore deposits, or rather of the metals, as for this purpose it is hardly necessary to take into account their state of combination; furthermore it is obvious that the characters and distribution of the great class of secondary deposits have no bearing on the point: it is with primary ores alone that we are concerned. Now most primary ores are either native metals, oxides, or sulphides—in some instances arsenic also seems to play the part of an electronegative element, as in enargite and several nickel and cobalt minerals and in arsenopyrite. Furthermore, most primary ores are of very simple composition: the more complex minerals are mostly found in the oxidized ores and in those of the zone of secondary enrichment, with which we are not here concerned.

The primary facts that we have to start on are somewhat as follows:

1. It has been shown that certain metals and non-metallic elements are found chiefly in the basic rocks, including especially nickel, cobalt, chromium, platinum, titanium, with chlorine, phosphorus, vanadium, and sulphur. Iron sulphides, often nickeliferous, are common.

2. Of these, chromium and platinum are specially characteristic of the ultrabasic rocks, themselves usually differentiates of basic magmas.

3. In connection with the extreme differentiation phases of acid magmas are found especially tin, tungsten, molybdenum, zirconium, uranium, lithium, with fluorine, boron, and abundance of water.

4. The rare earths of the thorium-cerium group are found chiefly in pegmatitic phases of granitic and syenitic magmas.

5. Iron, gold, silver, and copper are of more general distribution, without much tendency to characterize any special type of magma. Iron, however, shows a difference of combination: in the basic rocks it is largely combined with sulphur, titanium, or chromium, in the acid rocks it concentrates mainly as magnetite. Primarily copper is generally combined with sulphur, less commonly with arsenic, wherever it is found.

6. It appears that in the earliest stages of earth history known to us there were two primary magmas, granitic and basaltic: from these the other existing rock types were derived by differentiation.

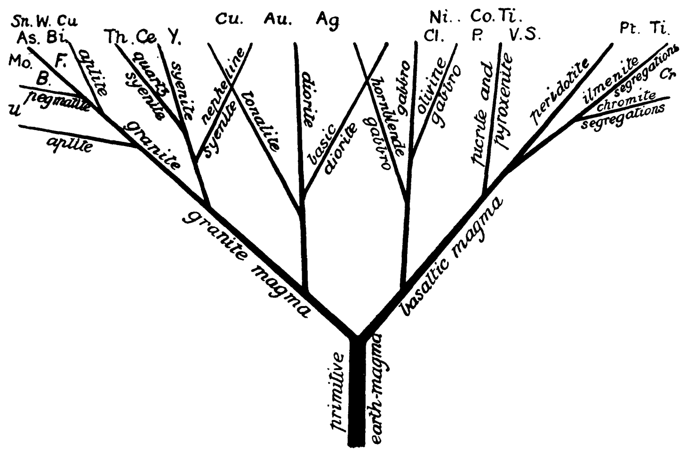

FIG. 1.—Genealogical tree illustrating conceptions of differentiation of igneous rocks and ore deposits from primitive magma.

It is a fair inference that earlier still there was one primitive earth magma of intermediate composition, perhaps a siliceous immiscible fraction, separated from a mainly metallic fraction that formed the heavy core of the earth. In this primitive silicate magma all the valuable metals were at first in solution, afterward separating into its various differentiated fractions according to their partition coefficients, or their degrees of solubility—no doubt assisted by gravity-sinking and fractional crystallization. Some metals seem to have been more or less soluble in all magmas, while others had very decided preferences for a particular type.

It is on the basis of these principles that the genealogical tree here presented (Fig. 1) has been constructed. In its essential

features it is similar to a diagram already published by the writer.[1] The present form of it is, however, slightly more elaborate and the various branches have been arranged in accordance with the silica percentage of the rocks, although the figure must not be regarded as drawn strictly to scale. It is also to be remarked that the thickness and length of the branches do not bear any relation to the actual abundance of the different rock types: in this respect the figure is purely diagrammatic and not quantitative. The angles of inclination between the various branches are controlled only by convenience of drawing. The intercrossing of various branches is, however, intentional, in order to show that similar final products may be obtained from different partial magmas. That is to say that similar rocks and ore types may have different chains of descent from a common ancestor. This is analogous to the biological phenomenon known as heterogeneous homoeomorphy.

This diagram, when looked at from this point of view, is in fact a basis for a truly genetic classification of certain large groups of primary ores; nevertheless it must be regarded as strictly limited in its scope. It takes no account of the secondary ores, or of certain groups which may be of supergene origin, formed by the action of descending meteoric waters. With these classes we are not now concerned. But it is claimed that this systematic arrangement does throw some light on the origin and genetic relationship of the great classes of primary ores, which are of fundamental importance, as being in all probability the original source of all the workable metallic deposits of the globe.

In this treatment of the subject it is necessary to take into account also the conceptions of metallogenetic epochs and metallogenetic provinces, which have been so ably worked out of late years by many writers, especially in America. If the whole scheme of differentiation as here outlined is regarded as continuous, a false impression will be obtained. On the contrary, the processes are discontinuous both in time and space. An admirable summary of the present state of our knowledge of the chronology of ore

[1] Rastall, "Differentiation and Ore-Deposits," *Geological Magazine*, Vol. LVII (1920), p. 298.

deposits will be found in the last chapter of the new edition of Lindgren's *Mineral Deposits*. From this it is clear that the type of mineralization here considered is mainly restricted in time to three periods, pre-Cambrian, Permo-Carboniferous, and Tertiary, corresponding to the greater periods of crustal disturbance and mountain-building. Of these the first is certainly complex and of great length, probably including several periods comparable in magnitude to the two later ones, but as yet it is hardly possible to disentangle these clearly in most parts of the world. The Canadian shield is an exception.[1] Here several distinct periods are distinguishable. Nevertheless it must be remembered that although the now visible manifestations, including the actual deposition of the ores, were spasmodic, the genetic processes are undoubtedly in constant operation in depth, elaborating the material and preparing the way for the igneous outbreaks and accompanying ore-formation that occur whenever the static equilibrium of the crust is disturbed, whatever may be the cause to which these disturbances are due. This is a fundamental question into which we cannot now enter.

[1] See Miller and Knight, *Trans. Roy. Soc. Canada*, Vol. IX (1915), pp. 241–49.